Theory of impurity effects on transport driven by micro-tearing mode (MTM) in the strong gradient pedestal of tokamak plasmas

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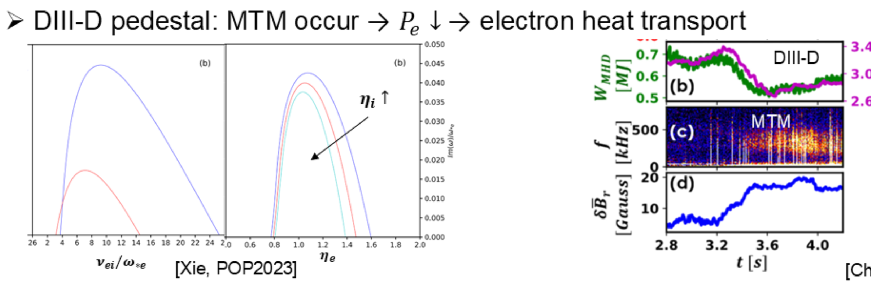
Impurity effects on MTM in the pedestal

- Impurity effects → MTM instability → electron heat transport
  - Collisionality $\nu_{ei}\uparrow \to \gamma_{MTM}$ first ↑ then ↓: for impurity, $Z_{eff}\uparrow \to \nu_{ei}\uparrow$
  - Gradient ratio $\eta_i\uparrow \to \gamma_{MTM}\downarrow$: stronger dilution effects for $\nabla n_z \to L_{ni}\downarrow \to \eta_i\uparrow$
  - DIII-D pedestal: MTM occur → $P_e\downarrow$ → electron heat transport



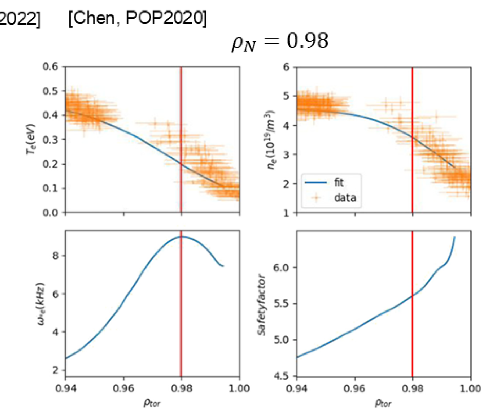
[Xie, POP2023] [Chen, POP2021]

Studying the impurity effects on MTM is helpful for understanding the electron heat transport

Ordering: based on pedestal parameters on DIII-D

- DIII-D strong gradient pedestal parameters dominated by MTM [Curie, NF2022] [Chen, POP2020]

Pulse	q	T_e (keV)	$n_e(10^{19}\ m^{-3})$	$\nu_{ei}(c_s/a)$
175823	5.59	0.197	3.57	7.38
ρ_{tor}	$\hat{s}$	a/L_{T_e}	a/L_{n_e}	$\beta(10^{-4})$
0.98	4.94	37.0	17.1	7.24
R (m)	a(m)	B_0 (T)	ρ_s (mm)	c_s (km s^{-1})
1.73	0.739	1.977	1.023	69.1
Ω_E (c_s/a)				
9362				



- Based on these parameters, orderings:

$$\frac{\omega}{\omega_{*e}}\sim\frac{\nu_{ei}}{\omega_{*e}}\sim 1,\ \hat{\beta}_e\gg 1$$

$$\hat{\beta}_e\equiv(\beta_e/2)L_s^2/L_{ne}^2\approx 3.5,\quad \omega_{*e}=-nqT_e/eBL_{ne}r,\quad \nu_{ei}=\frac{n_e e^4\ln\Lambda}{(4\pi\varepsilon_0)^2}m_e^2(2v_{te}^2)^{3/2},\quad \frac{\omega}{\omega_{*e}}\approx 5.4,\ \frac{\nu_{ei}}{\omega_{*e}}\approx 3.1$$

Perturbed density in slab configuration

- Perturbed distribution function of electron : drift kinetic equation [Xie, POP2023]

$$(\omega-k_\parallel v_\parallel)\delta f_e - iC_{ei}(\delta f_e)=\hat{\omega}_{*e,T}F_{Me}\frac{e}{T_e}(\delta\phi-v_\parallel\delta A_\parallel)-iF_{Me}\frac{e}{T_e}v_\parallel\delta E_\parallel$$

  - Lorentz gas (electron–ion) collision operator $C_{ei}(\delta f_e)=(1/2)\nu_{ei}(\partial/\partial\xi)(1-\xi^2)(\partial/\partial\xi)\delta f_e$
  - $\frac{\partial}{\partial\xi}(1-\xi^2)\frac{\partial}{\partial\xi}P_n(\xi)=-n(n+1)P_n(\xi)$ → expand δf_e as $\delta f_e=\sum_{n=0}h_n(v_e)P_n(\xi)$
- Perturbed parallel current density : $\delta j_\parallel=-e\int d^3v\,\delta f_e\xi v_e=-e\int d^3v\,h_1P_1(\xi)\xi v_e=\sigma_\parallel\delta E_\parallel$
- Perturbed electron density : $\delta n_e=\int d^3v\,\delta f_e=n_0\frac{\omega_{*e}}{\omega}\frac{e}{T_e}\delta\phi-\frac{k_\parallel}{e\omega}\sigma_{\parallel e}\delta E_\parallel$
  - Impurity terms → parallel electron conductivity $\sigma_{\parallel e}$ → δn_e
- Perturbed ion/impurity density: GK equation → $\delta n_s=-Z_s\tau_s n_{0s}\left\{\frac{\omega_{*s}}{\omega}+\left[1-\frac{\omega_{*s}}{\omega}(1+\eta_s)\right]b_s\right\}\frac{e}{T_e}\delta\phi$
- $\delta n_e=\delta n_i+Z\delta n_z$ + parallel Ampere's law → EM eigen-equation with impurity

General solution of eigen-equation in the ion region $x\sim\rho_i$

- Eigen-equation of $\hat{J}(k)$ when $\hat{k}\to 0$

$$\hat{k}=k\rho_{cs},\ \rho_{eff}^2/\rho_{cs}^2=\sum_{s=i,z}\frac{m_s}{m_i}\frac{f_s}{Z_s},\ K_{eff}=\sum_{s=i,z}\frac{m_s}{m_i}\frac{f_s}{Z_s}\frac{1}{Z_s\tau_s}\frac{L_{ne}}{L_{ns}}(1+\eta_s)$$

$$\frac{d}{dk}\left[\frac{(1-\hat{\omega}^{-1})+(\rho_{eff}^2/\rho_{cs}^2+K_{eff})\hat{k}^2}{(\rho_{eff}^2/\rho_{cs}^2+K_{eff})\hat{k}^2}\frac{d\hat{J}}{dk}\right]+\left(\frac{1}{4}-\mu^2\right)\frac{d\hat{J}}{dk}=0 \quad \xrightarrow{y=-\kappa^2\hat{k}^2,\ \kappa^2=\frac{\rho_{eff}^2/\rho_{cs}^2+K_{eff}}{(1-\hat{\omega}^{-1})}}$$

$$\hat{J}(k)=a_1\,{}_2F_1\left(-\frac{1}{4}+\frac{\mu}{2},-\frac{1}{4}-\frac{\mu}{2};-\frac{1}{2};y\right)+a_2y^{3/2}{}_2F_1\left(\frac{5}{4}+\frac{\mu}{2},\frac{5}{4}-\frac{\mu}{2};\frac{5}{2};y\right)$$

$$\hat{J}(k)\approx a_1\left(1-\frac{1-4\mu^2}{8}y\right)+a_2y^{3/2}$$

with $\frac{1}{4}-\mu^2=\frac{\hat{\omega}^2\hat{\beta}_e}{1+Z_{eff}\tau_i}\left(\frac{1}{\hat{\omega}}+Z_{eff}\tau_i\right)\left(1-\frac{1}{\hat{\omega}}\right)(\tau_i=\tau_z),\ Z_{eff}=f_i+Z^2f_z,\hat{\omega}=\omega/\omega_{*e}$

  - Boundary condition: matching to the MHD region

$$\hat{J}(k)\approx 1-\frac{1-4\mu^2}{8}\hat{k}^2+\frac{\pi}{3\Delta'\rho_{cs}}\hat{\beta}_e\hat{\omega}^2\left(\frac{\rho_{eff}^2}{\rho_{cs}^2}+K_{eff}\right)\hat{k}^3 \longrightarrow \frac{a_2}{a_1}=\frac{i\pi\hat{\beta}_e\hat{\omega}}{3\Delta'\rho_{cs}\kappa^3}\left(\hat{\omega}\frac{\rho_{eff}^2}{\rho_{cs}^2}+K_{eff}\right)$$ [Pegoraro, POF1989]

- For $\hat{k}\to\infty$, the general solution of $\hat{J}(\hat{k})$ can get

$$\hat{J}(k)\sim y^{1/4-\mu/2}\left[a_1\frac{\Gamma(-1/2)\Gamma(-\mu)}{\Gamma^2(-1/4-\mu/2)}-ia_2\frac{\Gamma(5/2)\Gamma(-\mu)}{\Gamma^2(5/4-\mu/2)}\right]+y^{1/4+\mu/2}\left[a_1\frac{\Gamma(-1/2)\Gamma(\mu)}{\Gamma^2(-1/4+\mu/2)}-ia_2\frac{\Gamma(5/2)\Gamma(\mu)}{\Gamma^2(5/4+\mu/2)}\right]$$

i.e. $\hat{J}(k)\sim\hat{a}_+k^{1/2+\mu}+\hat{a}_-k^{1/2-\mu}$ ⇒

$$\frac{\hat{a}_-}{\hat{a}_+}=\left[-\frac{\rho_{eff}^2/\rho_{cs}^2+K_{eff}}{(1-\hat{\omega}^{-1})}\right]^{-\mu}\frac{\Gamma(-\mu)}{\Gamma(\mu)}\frac{\frac{1}{\Gamma^2(-\mu/2-1/4)}+i\frac{3}{8}\frac{a_2}{a_1}\frac{1}{\Gamma^2(-\mu/2+5/4)}}{\frac{1}{\Gamma^2(\mu/2-1/4)}+i\frac{3}{8}\frac{a_2}{a_1}\frac{1}{\Gamma^2(\mu/2+5/4)}}$$

General solution of eigen-equation in the electron region $x\sim\delta$

- Eigen function of $J(s)$ for $s=x/\delta\to\infty$

$$\delta^2=\exp(-i\pi/2)\frac{2\omega\nu_e}{k_y^2v_{the}^2}L_s^2=e^{-i\frac{\pi}{2}}\hat{\omega}\delta_0^2$$

$$\frac{d^2}{ds^2}\left\{\left[\frac{(1+\hat{d}_0s^2+\hat{d}_1s^4)}{(\sigma_0+\sigma_1s^2)}\right]J(s)\right\}=-\hat{\beta}_T\hat{\omega}^2J(s)\xrightarrow{\bar{J}=\frac{J}{\bar{\sigma}}}s^2\frac{d^2}{d^2s}\bar{J}=\left(-\frac{s_t^2}{s^2}-\mu^2+\frac{1}{4}\right)\bar{J}\ \text{with}\ s_t^2=-\hat{\beta}_T\hat{\omega}^2\frac{\sigma_0}{\hat{d}_1},(\nu_{ei}\gg\omega)$$

⇒ $\bar{J}=a_1\sqrt{\frac{S}{S_t}}I_\mu\left(\frac{S_t}{s}\right)+b_1\sqrt{\frac{S}{S_t}}K_\mu\left(\frac{S_t}{s}\right)$

  - Boundary condition: for $s\to 0$, $J(s)$ is finite → $\bar{J}=\sqrt{\frac{S}{S_t}}K_\mu\left(\frac{S_t}{s}\right)$
- The general solution of $J(s)$ for $s\to\infty$: $J(s)\sim b_+s^{-3/2+\mu}+b_-s^{-3/2-\mu}$ with $\frac{b_-}{b_+}=-\left(\frac{s_t}{2}\right)^{2\mu}\frac{\Gamma(1-\mu)}{\Gamma(1+\mu)}$
  - Fourier transformation between $s\to t=\delta k$: $\hat{J}(t)\sim\hat{c}_+t^{1/2+\mu}+\hat{c}_-t^{1/2-\mu}$ with $\frac{\hat{c}_-}{\hat{c}_+}=\frac{b_-}{b_+}\frac{\Gamma\left(-\frac{1}{2}+\mu\right)}{\Gamma\left(-\frac{1}{2}-\mu\right)}\tan\left[\frac{\pi}{2}\left(\frac{1}{2}+\mu\right)\right]$

⇒ $$\frac{\hat{c}_-}{\hat{c}_+}=-\left(\frac{2}{s_t}\right)^{2\mu}\frac{\Gamma(\mu-1/2)\Gamma(1+\mu)}{\Gamma(-\mu-1/2)\Gamma(1-\mu)}\tan\left[\frac{\pi}{2}\left(\frac{1}{2}+\mu\right)\right]$$

Dispersion relation of MTM with impurity

- Matching $\hat{J}(k)$ in ion region and $\hat{J}(t)$ in electron region: $\frac{\hat{c}_-}{\hat{c}_+}=\frac{\hat{a}_-}{\hat{a}_+}\left(e^{-i\pi/4}\frac{\hat{\omega}^{1/2}\delta_0}{\rho_{cs}}\right)^{2\mu}$

⇒ $$e^{i\frac{\pi}{2}}R^\mu=\frac{\mu+\frac{1}{2}}{-\mu+\frac{1}{2}}\frac{\Gamma^2(-\mu)}{\Gamma^2(\mu)}\frac{\mathcal{D}-\cot\left[\pi\left(\frac{1}{4}+\frac{\mu}{2}\right)\right]}{\mathcal{D}-\cot\left[\pi\left(\frac{1}{4}-\frac{\mu}{2}\right)\right]}$$

with $R=16\frac{d_1}{1.71\eta_e}\frac{\rho_{cs}^2}{\delta_0^2}\frac{\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff}}{1/4-\mu^2}$, $\mathcal{D}=\frac{2}{\pi}\Delta'\rho_{cs}\frac{(\rho_{cs,eff}^2/\rho_{cs}^2)^{1/2}}{(\hat{\omega}-1)^{1/2}}\frac{\Gamma(5/4-\mu/2)\Gamma(5/4+\mu/2)}{\Gamma(3/4-\mu/2)\Gamma(3/4+\mu/2)}$

- Assuming $\hat{\omega}\approx 1+\delta\hat{\omega}$ and $\mu\approx 1/2-\hat{\beta}_e\delta\hat{\omega}$, get the real frequency and growth rate

$$\delta\hat{\omega}_r=\frac{2}{\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff}}\left(\frac{1}{\hat{\beta}_e\Delta'\rho_{cs}}\right)^2+\frac{2\sqrt{2}}{\hat{\beta}_e^{3/2}\Delta'\rho_{cs}(\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff})}\left(\frac{1.71\eta_e}{d_1}\right)^{1/2}\frac{\delta_0}{\rho_{cs}}$$

$$\hat{\gamma}=-4\frac{1}{\hat{\beta}_e\Delta'\rho_{cs}(\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff})}\frac{\delta_0}{\rho_{cs}}\left(\frac{1.71\eta_e}{d_1}\right)^{1/2}\left[1+\sqrt{2}\Delta'\rho_{cs}\hat{\beta}_e\frac{\delta_0}{\rho_{cs}}\left(\frac{1.71\eta_e}{d_1}\right)^{1/2}\right]$$

Dispersion relation of MTM with impurity

- The real frequency and growth rate

$$\hat{\omega}_r=1+\frac{2}{\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff}}\left(\frac{1}{\hat{\beta}_e\Delta'\rho_{cs}}\right)^2+\frac{2\sqrt{2}}{\hat{\beta}_e^{3/2}\Delta'\rho_{cs}(\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff})}\left(\frac{1.71\eta_e}{d_1}\right)^{1/2}\frac{\delta_0}{\rho_{cs}}$$

$$\hat{\gamma}=-4\frac{1}{\hat{\beta}_e\Delta'\rho_{cs}(\rho_{cs,eff}^2/\rho_{cs}^2+K_{eff})}\frac{\delta_0}{\rho_{cs}}\left(\left|\frac{\sigma_0}{d_1}\right|\right)^{1/2}\left(1+\sqrt{2}\Delta'\rho_{cs}\hat{\beta}_e\frac{\delta_0}{\rho_{cs}}\sqrt{\left|\frac{\sigma_0}{d_1}\right|}\right)$$

with $\rho_{eff}^2/\rho_{cs}^2=\sum_{s=i,z}\frac{m_s}{m_i}\frac{f_s}{Z_s}\approx 1$ (fully ionized light impurity), $K_{eff}=\sum_{s=i,z}\frac{m_s}{m_i}\frac{f_s}{Z_s}\frac{1}{Z_s\tau_s}\frac{L_{ne}}{L_{ns}}(1+\eta_s)$, $\delta_0^2=\frac{2\nu_{ei}}{k_y^2v_{the}^2}L_s^2$

  - For MTM, $\Delta'<0\to\hat{\omega}_r,\ \hat{\gamma}>0$, an unstable mode
  - ν_{ei} is a drive factor of MTM, with $\nu_{ei}\uparrow$, $\hat{\gamma}$ first increases and then decreases
  - Impurity effects: $\rho_{cs,eff},K_{eff}\uparrow$, MTM is stabilized; $Z_{eff}\uparrow\to\nu_{ei}\uparrow$
  - In high $\hat{\beta}_e$ plasma, MTM is stabilized

Electron heat transport flux driven by MTM

- The electron energy flux driven by MTM with impurity $Q_e=\mathrm{Re}\left\langle\int d^3v\frac{1}{2}m_e(v_\parallel^2+v_\perp^2)\delta f_e\left(\mathbf{B}\times\frac{\delta\phi-v_\parallel\delta A_\parallel}{B^2}\right)\right\rangle$
  - The δf_e can be expressed as $\delta f_e=(\chi_{e,e}^{ES}\delta\hat{\phi}+\chi_{e,e}^{EM}\delta\hat{A}_\parallel)F_{0e}$

⇒ $Q_e=-\sum_k\chi^{tot}n_{0e}\nabla T_{0e}|\delta\hat{\phi}_k|^2+\sum_k\kappa^{tot}\nabla n_{0e}T_{0e}|\delta\hat{\phi}_k|^2+\sum_kV^{tot}n_{0e}T_{0e}|\delta\hat{\phi}_k|^2=Q_{e,\phi\phi}+2Q_{e,\phi A}+Q_{e,AA}$

- The energy flux also includes which induced by particle convection:

$$Q_{e\Gamma}=\mathrm{Re}\left\langle\int d^3v\frac{3}{2}T_{0e}\delta f_e\left(\mathbf{B}\times\frac{\nabla\delta\phi-v_\parallel\nabla\delta A_\parallel}{B^2}\right)\right\rangle$$

- The net electron heat flux: $q_e=Q_e-Q_{e\Gamma}$, and effective election heat conductivity:

$$\chi_e^{eff}=-\frac{q_e}{n_{0e}\nabla T_{0e}}=\left\{\frac{33}{4}\frac{\gamma_k}{(\omega_r)^2}+6\frac{\gamma_k}{(\omega_r+\omega_s)^2}\left[1-\frac{\omega_s}{\omega_r-\omega_{*e}\left(1+\frac{3}{2}\eta_e\right)}\right]+3\frac{\omega_r\gamma_k}{(\omega_r+\omega_s)^2}\left[1-\frac{\omega_s}{\omega_r}-\frac{2\omega_s}{\omega_r-\omega_{*e}\left(1+\frac{3}{2}\eta_e\right)}\right]\right\}(k_\theta\rho_{ce}c_s)^2|\delta\hat{\phi}_k|^2$$

(terms: $\chi_{\phi\phi}^{eff}$, $2\chi_{\phi A}^{eff}$, χ_{AA}^{eff})

Particle transport flux driven by MTM

- The electron flux driven by MTM with impurity $\Gamma_e=\mathrm{Re}\left\langle\int d^3v f_e\left(\mathbf{B}\times\frac{\nabla\delta\phi-v_\parallel\nabla\delta A_\parallel}{B^2}\right)\right\rangle=\Gamma_e^{E\times B}+\Gamma_e^{Fl}$
  - The effective electron diffusive transport coefficient

$$D_e^{eff}=-\frac{\Gamma_e}{\nabla n_e}=(k_\theta\rho_{ce}c_s)^2\left\{\frac{2\gamma_k}{(\omega_r)^2}+\frac{2\gamma_k}{(\omega_r+\omega_s)^2}+\frac{\gamma_k}{(\omega_r+\omega_s)^2}\frac{\omega_r-\omega_s}{\omega_r+\omega_s}+\frac{3}{2}\frac{L_{ne}}{L_{Te}}\left[\frac{\gamma_k}{(\omega_r)^2}+\frac{\gamma_k}{(\omega_r+\omega_s)^2}\left[2+\frac{\omega_r-\omega_s}{\omega_r+\omega_s}\right]\right]+\frac{L_{ne}}{k_\theta\rho_{ce}c_s}\frac{4\gamma_k}{(\omega_r+\omega_s)^2}\left[\omega_s-\frac{\omega_s^2}{\omega_r+\omega_s}\right]\right\}|\delta\hat{\phi}_k|^2$$

  - D_e^{eff} is much smaller than χ_e^{eff}: $D_e^{eff}/\chi_e^{eff}\sim 0.1$ [Kotschenreuther, NF2019]
- Non-Ambipolarity of MTM particle transport
  - As $f_s=-Z_s\tau_s\frac{\omega_{*s}}{\omega}\left[1+\eta_s(\hat{v}_s^2-3)/2\right]F_{0s}\delta\hat{\phi}_k$, the ion/impurity flux: $\Gamma_s=\left\langle\int d^3v\delta f_s\left[\mathbf{B}\times\nabla(\delta\phi-v_\parallel\delta A_\parallel)/B^2\right]\right\rangle=\Gamma_s^{E\times B}+\Gamma_s^{Fl}=\Gamma_s^{E\times B}$

⇒ $\Gamma_s^{E\times B}=-\sum_k\frac{\gamma_k'}{(\omega_r')^2}\left\{(1-b_s)\nabla n_s+\frac{b_s}{L_{Ts}}n_{0s}\right\}k_\theta^2\rho_{cs}^2c_s^2|\delta\hat{\phi}_k|^2$

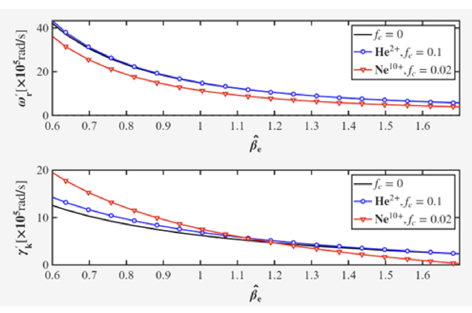
  - Quasi-neutrality condition → $\Gamma_i^{E\times B}+Z\Gamma_z^{E\times B}-\Gamma_e^{E\times B}=0$
  - Γ_e^{Fl} can not be compensated, i.e. the ambipolarity is not satisfied intrinsically for electromagnetic MTM turbulence

$\hat{\beta}_e$ on MTM instability

$$\hat{\omega}_r=1+\frac{2}{\rho_{eff}^2/\rho_{cs}^2+K_{eff}}\left(\frac{1}{\hat{\beta}_e\Delta'\rho_{cs}}\right)^2+\frac{2\sqrt{2Z_{eff}\hat{\nu}_{e0}\eta_e}}{\hat{\beta}_e^{3/2}\Delta'\rho_{cs}(\rho_{eff}^2/\rho_{cs}^2+K_{eff})}C_{\nu\eta}\qquad \hat{\gamma}=-4\frac{\sqrt{Z_{eff}\hat{\nu}_{e0}\eta_e}}{\hat{\beta}_e\Delta'\rho_{cs}(\rho_{eff}^2/\rho_{cs}^2+K_{eff})}C_{\nu\eta}\left(1+\sqrt{2Z_{eff}\hat{\nu}_{e0}\eta_e}\Delta'\rho_{cs}\hat{\beta}_eC_{\nu\eta}\right)$$

with $\hat{\beta}_e\equiv(\beta_e/2)L_s^2/L_{ne}^2$, $K_{eff}=\sum_{s=i,z}\frac{m_s}{m_i}\frac{f_s}{Z_s}\frac{1}{Z_s\tau_s}\frac{L_{ne}}{L_{ns}}(1+\eta_s)\approx f_iL_{ei}(1+\eta_i)+f_zL_{ez}(1+\eta_z)$, $C_{\nu\eta}=\left(\frac{1.71}{d_1}\right)^{1/2}\sqrt{\frac{\hat{\omega}_0}{2}}\frac{1}{k_y\rho_{cs}}\frac{L_s}{a}\sqrt{\frac{m_e}{m_i}}$, $\hat{\omega}_{*e}=\frac{\omega_{*e}}{c_s/a}=k_y\rho_{cs}\frac{a}{L_{ne}}$

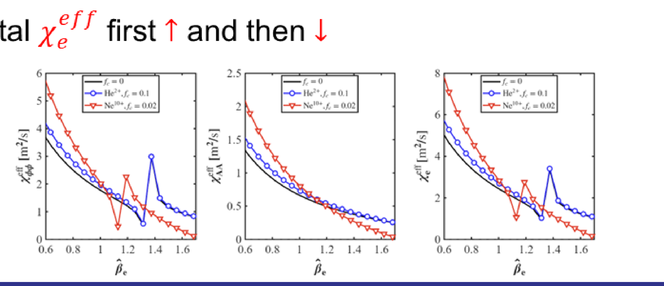
- $\hat{\beta}_e\uparrow$: $\beta_e\uparrow$ or $a/L_{ne}\uparrow$
- When $f_c=0$, $\hat{\beta}_e\uparrow\to\omega_r,\gamma_k\downarrow$: from 0.6 to 0.9, ω_r decreases about 59%, γ_k decreases about 58%
- When $Zf_c=0.2$, $A_z(Z)\uparrow\to\omega_r\downarrow$: $Z_{eff}\uparrow$ is more dominant than the $K_{eff}\downarrow$; for small $\hat{\beta}_e$, $A_z(Z)\uparrow\to\gamma_k\uparrow$, and opposite for large $\hat{\beta}_e$



$\hat{\beta}_e$ on electron heat conductivity

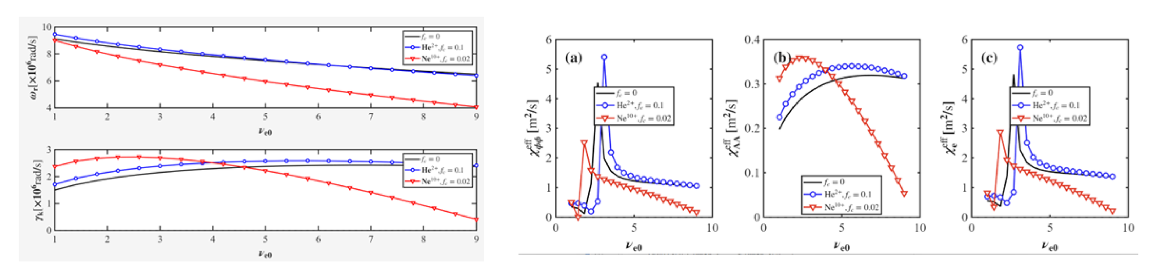
$$\chi_e^{eff}=\left[\frac{33}{4}\frac{\gamma_k}{(\omega_r)^2}+3\frac{\gamma_k}{(\omega_r+\omega_s)^2}\right](k_\theta\rho_{ce}c_s)^2|\delta\hat{\phi}_k|^2\qquad |\delta\hat{\phi}|=\frac{e}{T_e}\left|\frac{ic^2k_\perp^2\frac{\nu_{ei}}{\omega_{pe}^2\sigma}+\omega}{k_\theta k_\parallel}\right|\delta B_r=\frac{e}{T_e}\left|\frac{\omega_s+\omega}{k_\theta k_\parallel}\right|\delta B_r\qquad \omega_s=k_\perp^2d_e^2\frac{\nu_{ei}}{\sigma_i}=-k_\perp^2d_e^2\frac{k_\parallel^2v_{the}^2}{\omega_r-\omega_{*e}\left(1+\frac{3}{2}\eta_e\right)}$$

- $\chi_{\phi\phi}^{eff}$ is largest, χ_{AA}^{eff} is about half of $\chi_{\phi\phi}^{eff}$
- $\beta_e\uparrow\to\chi_{\phi\phi}^{eff}\downarrow$: due to the decrease of $|\delta\hat{\phi}|^2$ is more evident, and $\chi_{\phi\phi}^{eff}$ jumps when the reduced ω_r causes ω_s to switch from positive to negative; $\chi_{AA}^{eff}\downarrow$: $\gamma\downarrow$
- $A_z(Z)\uparrow\to$ total χ_e^{eff} first ↑ and then ↓



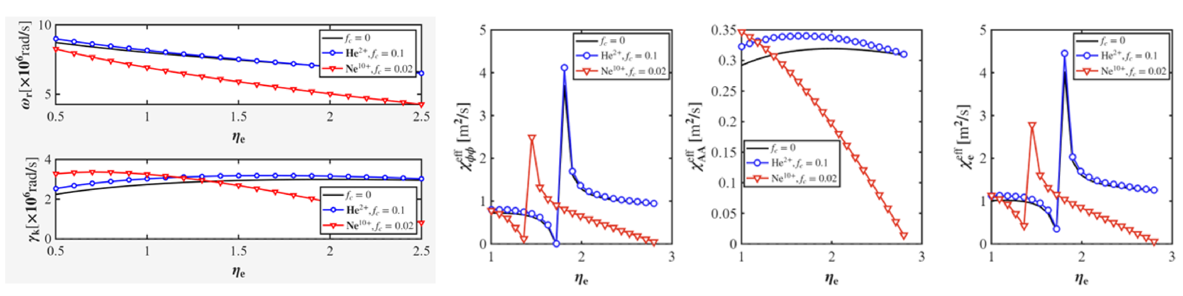
Driven parameters: collisionality ν_{ei}

- $\nu_{e0}\uparrow\to\omega_r\downarrow$, while γ_k increase first and then decrease
- $A_z(Z)\uparrow$: for small ν_{e0}, $A_z(Z)\uparrow\to\gamma_k\uparrow$, and opposite for large ν_{e0}
- $\nu_{e0}\uparrow\to\chi_{\phi\phi}^{eff}\downarrow$: because the decrease of $|\delta\hat{\phi}|^2$ is more evident; χ_{AA}^{eff} increase first and then decrease



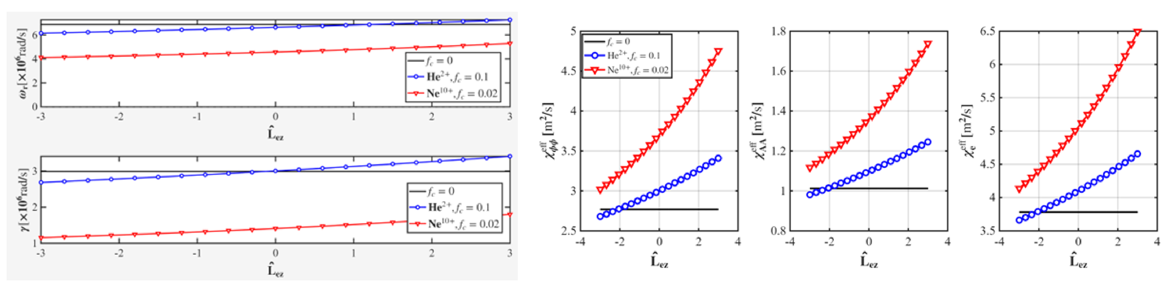
Driven parameters: electron temperature gradient η_e

- $\eta_e\uparrow\to\omega_r\downarrow$, while γ_k increase first and then decrease
- When $Zf_c=0.2$, $A_z(Z)\uparrow\to\omega_r\downarrow$; for small η_e, $A_z(Z)\uparrow\to\gamma_k\uparrow$, and opposite for large $\hat{\beta}_e$
- $\eta_e\uparrow\to\chi_{\phi\phi}^{eff}\downarrow$: because the decrease of $|\delta\hat{\phi}|^2$ is more evident; χ_{AA}^{eff} first ↑ and then ↓



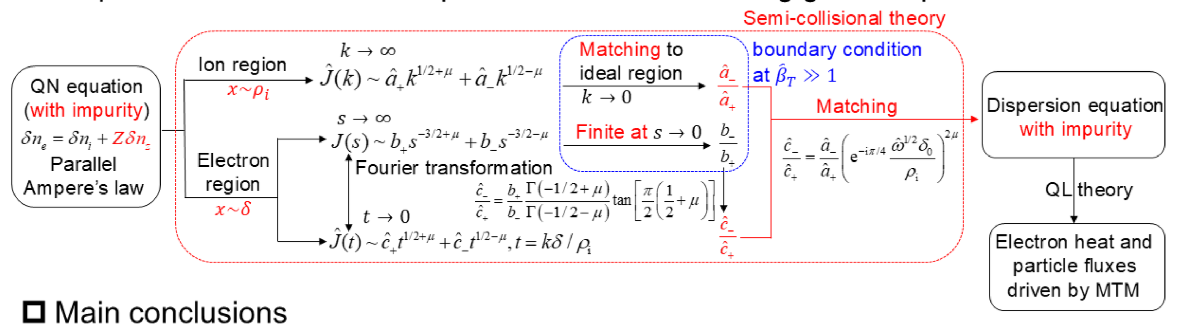
Impurity parameters: $\hat{L}_{ez}(a/L_{ne}=17.1)$

- Besides the type of the impurity, the impurity profile ($\hat{L}_{ez}$) can also affect the MTM and the transport
- $a/L_{nz}\uparrow\to\hat{L}_{ez}\uparrow\to K_{eff}\downarrow$, $\omega_r,\gamma_k\uparrow$
- $\hat{L}_{ez}\uparrow\to$ total $\chi_e^{eff}\uparrow$: because $\gamma_k\uparrow$



4. Summary

- Dispersion relation and transport fluxes at DIII-D strong gradient pedestal:



- Main conclusions
  - $\nu_{ei}\uparrow$ can make $\omega_r\downarrow$ and γ_k increase first then decrease, $\hat{\beta}_e\uparrow$ can stabilize MTM
  - MTM dominates electron heat transport in the pedestal, as $D_e^{eff}/\chi_e^{eff}\sim 0.1$, and $\chi_{\phi\phi}^{eff}$ is largest
  - $\nu_{ei}\uparrow$ and $\hat{\beta}_e\uparrow$ both enhance the electron heat transport

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